

Co-designing a citizen science climate service

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ABSTRACT

Interactive mobile technologies provide an emerging opportunity for citizens to engage with and enhance urban climate resilience, both as providers of locally situated data on climate variables, impacts and climate adaptation measures as well as to obtain information on local conditions and recommendations.

This paper examines the process of co-designing a citizen science application for urban climate resilience in four European cities. Further, the paper studies if and how the system enables knowledge co-production to increase urban resilience following process principles for co-production of climate services and discusses the legitimacy, transparency, credibility, and relevance of the process. We further assess the role that a citizen science climate service could play as a boundary object in knowledge co-production. We draw on experiences from a co-design process that included municipal stakeholders from different sectors as well as municipal employees and civil society end-users involved in campaigns. This study identified a set of barriers and enablers for the co-design process and concludes that the CitizenSensing application can fulfil the role of a boundary object, but that the co-design process is a balancing act between navigating time constraints, including stakeholders' different and changing demands and perspectives while retaining a high level of flexibility and reflexivity.

Practical Implications

This study examines the co-design process of a citizen science climate service to support urban citizens and authorities in preparing for and responding to local climate impacts. We analyze the findings of the Citizen Sensing project, which involved stakeholders and citizens in a collaborative process in four European pilot cities – Porto (Portugal), Rotterdam (Netherlands), Norrköping (Sweden) and Trondheim (Norway). The Citizen Sensing climate service consists of a mobile application, the *CitizenSensing app*, with which users can report observed weather events, climate impacts and add images and text. Users can additionally explore data from local sensors and refer to this data to comment and validate. The system further allows users to explore the local data shared by others, both in the app as well as on a web portal that facilitates a flexible exploration and filtering of collected information. We explore barriers and enablers for the co-design process and assess to what extent a citizen science climate service could function as a boundary object in climate adaptation efforts.

In terms of practical implications, this study provides the following insights:

- Co-designing a climate service that builds on citizen science requires an active collaboration with municipal stakeholders to outline criteria that are relevant for the local urban context, as well as in the identification and engagement of a variety of end-users. In this study, a high level of flexibility was required both in the research collaboration as well as in the design of the climate service to allow for the inclusion of multiple perspectives, as well as novel insights throughout the process. An important enabler for collaboration was the existence of municipal climate adaptation initiatives that facilitated a strong link to relevant ongoing processes.
- Barriers to the co-design process included time-constraints, due to the time frame of the project as well as in terms of the limited time availability of stakeholders and end-users. Another observed barrier were time constraints of stakeholders because of multiple ongoing

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projects and collaborations, and of end-users because of limited experienced relevance or even a negative side-effect of gamification.

- While standardization of the process across pilots aimed to enable comparisons, this became a trade-off with the flexibility and customization of the process to ensure relevance and inclusivity at each pilot. The same applied to the standardized format of the app, which included all key issues across pilots which led to a complexity that introduced a potential barrier for some users.

We conclude that co-designing a climate service that aims to include local expertise, experiences and engagement requires a carefully executed balancing act by both researchers and stakeholders. Key aspects that need to be acknowledged are the high demands of time, efforts, flexibility and reflexivity throughout the entire process, while ensuring that the full potential of the co-design process and the developed tool can benefit all involved partners.

1. Introduction

Climate change poses unprecedented impacts and challenges to the urban realm. Addressing these calls for better spatial coverage of locally situated data as well as new methods to engage and co-produce knowledge to inform and empower citizens, practitioners, and local authorities in taking adaptive actions and increasing urban climate resilience. In line with this, the co-production of climate services has been proposed to ensure the relevance, legitimacy and validity of developed services and knowledge, and to close the usability gap identified in existing services (European Commission, 2015; Klein and Juhola, 2014; Vincent et al., 2018). As a large body of recent scientific studies addresses the co-production of climate services, the diversity in approaches and conceptualizations of co-production becomes evident (e.g., Bremer and Meisch, 2017; Briley et al., 2015; Golding et al., 2017; Vaughan et al., 2018; Vollstedt et al., 2021). The involvement of citizens and practitioners can frame issues in ways that are more accurate, provide information that creates more relevant solutions, and potentially increase the legitimacy of processes (Fung, 2015). Deliberate co-production of climate science knowledge involves the planning and practice of collaborative scientist-stakeholder research with the aim of attaining usable scientific outcomes (Meadow et al., 2015; Vincent et al., 2018). Earlier studies pointed out that the success of knowledge co-production depends on two-way communication, long-term relationships (Kirchhoff et al., 2013), quality and extent of scientist-stakeholder interactions (Lemos et al., 2012) and the degree to which outcomes fit users' perceived knowledge and needs. Moreover, including reflexivity (Fazey et al., 2018) as part of the collaborative process by engaging both researchers and non-academic partners in assessments of e.g., research design, data collection and analysis, has been highlighted as an essential element to increase quality and robustness in transdisciplinary research.

Citizen science has a long tradition and spans across a vast number of scientific fields (Bonney et al., 2014; Kullenberg et al., 2016; Sauermann et al., 2020). To consolidate diverse definitions and delimitations of citizen science, the European Citizen Science Association, developed 'ten principles of citizens science' including the principle that citizen science refers to initiatives that "actively involve citizens in scientific endeavour that generates new knowledge or understanding" (European Citizen Science Association, 2015). Recent studies have focused on various aspects of digital participation and citizen engagement, exploring the role of crowd sourced geographical data and volunteered geographic information (Sui et al., 2013) in climate and sustainability sciences (e.g., Bouzguenda et al., 2019; Bremer et al., 2019; Ertö, 2015; Glaas et al., 2020; Meier et al., 2017; Pánek, 2018; van Etten et al., 2019). Employing digital tools in knowledge co-production processes bears potential for increased engagement and flexibility by allowing a wider scope of participants but also calls for a reflexive assessment of the role these tools have for collecting, sharing, and exploring data, in relation to co-creation and co-production processes (Cash and Belloy, 2020; Lember

et al., 2019). Digital tools in co-production processes can play the role of 'boundary objects', i.e., entities that span and bridge the boundary between 'social worlds, and facilitate communication across groups' (White et al., 2010: 221), and thus have the capacity to "translate across culturally defined boundaries" between different "communities of knowledge and practice" (Fox, 2011: 71), such as the producers and users of climate services (Cash et al., 2003; Hegger et al., 2012). As Hegger et al. (2012: 57) argue, "boundary objects can have a mediating role in the development of co-production narratives" and can hence play an important role in dialogues on e.g., urban climate resilience. Boundary objects in climate adaptation research can range from GIS mappings to strategic plans, concepts, or field visits (Hegger et al., 2012). In the example of a citizen science-based climate service, the role of boundary objects is to support a process of meaning making on climate adaptation and urban resilience, enabling the sharing of knowledge and experiences of multiple communities across different epistemologies (Fox, 2011; Star and Griesemer, 1989; Turnhout, 2009). The boundary itself relies on the principles of mediation, communication, and translation (Cash et al., 2003). Mediation ensures that the boundary is open to some influence and knowledge exchange (e.g., user requests) but closed to others (e.g., political interests). While effective communication requires translation of scientific information to be tailored for the user group, user perspectives and understanding must also be summarized and put into context to create meaning, clarity, and credibility. As such, boundary objects need to "allow for interpretative flexibility and to provide room for negotiation" (Hegger et al., 2012: 57).

This study critically explores the process of co-designing a citizen science climate service for knowledge co-production, drawing on the empirical case of the Citizen Sensing project. The project developed and assessed a web-based mobile application for citizen science in four European pilots. Drawing on an analytical framework outlining process principles for co-designing climate services (Vincent et al. 2018) and knowledge co-production (Cash et al., 2003; Hegger et al., 2012; Kirchhoff et al., 2013), this study analyses empirical findings guided by the following research questions: (i) To what extent was the co-design process collaborative, inclusive and flexible?; (ii) What barriers and enablers influenced the co-design process?; and (iii) What role did the citizen science climate service play as a boundary object in knowledge co-production?

2. Analytical framework

This study takes its analytical point of departure in literature on knowledge co-production in the field of climate science, specifically climate adaptation research, to identify and consolidate criteria for knowledge co-production that are relevant for climate service development. We discuss the process of co-designing a climate service, and the role of the climate service as a boundary object for knowledge co-production (Cash et al., 2003; Fox, 2011; Hegger et al., 2012; Turnhout, 2009; White et al., 2010).

While previous studies point out the function of climate services to raise awareness of climate issues (e.g., Kjellström et al., 2016), user uptake of such information to inform decision making remains limited (Jacobs and Street, 2020; Klein and Juhola, 2014; Lemos et al., 2012). The usability of climate science knowledge is a function of how it is produced and the context of its potential use. Earlier studies show that usability increases if knowledge is created in an iteration between producers and users (Dilling and Lemos, 2011) and if climate service outputs are tailored for specific locations or user requirements (Donnelly et al., 2018). An iterative process, moving back and forth between the scientific aims, user needs and context, is considered key to successful co-production of climate knowledge (Lemos and Morehouse, 2005).

Vincent et al. (2018) outlined three principles for the co-production process of climate services. The process should be *collaborative* i.e., "built upon inclusion of different people with different needs and different knowledge systems" and *inclusive*, ensuring "inclusion of users,

and their partnership in the process of producing a service”, to “help construct knowledge that is useful and usable” (Vincent et al., 2018: 49). *Flexibility* is also required because “as a result of continuous knowledge exchange, monitoring and learning, there may be need to refine product and process” (ibid). Table 1 presents how these three process principles are applied in this study.

In relation to these process principles, we reflect on key criteria for co-production processes, namely *legitimacy*, *relevance*, *transparency*, and *credibility* (Cash et al., 2003; Dilling and Lemos, 2011; Djenontin and Meadow, 2018; Hegger et al., 2012) to explore how these can guide the design of collaborative research processes and reveal barriers and enablers. While these criteria are frequently interrelated, we here outline their relevance in assessing the process of co-designing a climate service.

Legitimacy reflects that the processes and production of knowledge are respectful towards participants’ “divergent values and beliefs, unbiased in its conduct, and fair in its treatment of opposing views and interests” (Cash et al., 2003: 8086). In line with this, *relevance* relates to the focus and interests of participants and to what extent projects are respectful and inclusive of their perspectives and contextual circumstances and address their needs and expectations (Cash et al., 2003; Djenontin and Meadow, 2018; Hegger et al., 2012). In terms of collaboration, these two criteria support an analysis of the extent to which co-design processes can increase the relevance of research outcomes (Balazs and Morello-Frosch, 2013), co-produce usable science (Dilling and Lemos, 2011), increase the likelihood that the climate service matches decision makers’ needs (Jacobs and Street, 2020; Street, 2016; Williams et al., 2020), and how the collaborative process could maximize engagement for relevant outcomes (Akpo et al., 2015; Cvitanovic et al., 2015; Foley et al., 2017; Kirono et al., 2014; Kraaijvanger et al., 2016). Collaboration with stakeholders and users is central for research to create societally relevant knowledge (Funtowicz and Ravetz, 1993; Wiek et al., 2012). While inclusiveness is closely related to collaboration, it refers more specifically to the inclusion of diverse societal actors (e.g., representing various gender issues and norms). *Legitimacy* and *relevance* of the co-design process are critical elements to produce effective and relevant outcomes (Djenontin and Meadow, 2018; Hegger et al., 2012; Klopogge and Sluijs, 2006; Roux et al., 2006), and require clear communication of the information a climate service can provide, as well as its limitations and uncertainties (Donnelly et al., 2018). Flexibility in the co-design process can provide *legitimacy* and increase the experienced *relevance*, by allowing the inclusion of multiple perspectives (Cash et al., 2003). Dilling and Lemos (2011) argue that flexibility and risk-taking may be necessary in agenda-setting. As such, flexibility in terms of willingness to think across the science policy divide, inclusiveness of different epistemologies, as well as responsiveness of the

research team and agenda towards user needs have been outlined as essential (Dilling and Lemos, 2011; Lemos and Morehouse, 2005) for increasing the legitimacy and relevance of the research process and outcomes.

Transparency relates to the process itself and refers to the degree to which participants are involved in all parts of the co-design process, and can understand, share and contribute to details of the process and the outcomes (Keeys and Huemann, 2017; McCall and Dunn, 2012). *Credibility* “refers to the perceived adequacy of the knowledge produced” (Hegger et al., 2012:54) and the robustness of the process of data collection and analysis. In terms of collaboration, this might refer to the selection of methods and mode of communication, to ensure *transparency* of the co-design process. A common vocabulary is essential for clear communication (Donnelly et al., 2018). Similarly, inclusion of place-based knowledge in science (Hegger et al., 2012) increases credibility, and the inclusion of diverse actors encourages *transparency* in the dissemination of knowledge and outcomes. In flexible co-design processes, *transparency* is important if e.g., the climate service is continually adapted, to ensure that stakeholders and end-users, but also scientists can follow developments since it diverts from linear development and evaluation cycles.

3. Material and methods

3.1. The project

The Citizen Sensing project addresses the need of European cities and urban citizens for heightened knowledge of local conditions with consideration to climate change, to make more informed and site-specific decisions related to how to respond and adapt to climate-related risks such as extreme temperatures and heavy precipitation. The objective of the project was to assess if and how the service has potential to increase citizen engagement and to contribute to urban resilience. To meet this objective, the project co-designed a citizen science climate service for four European Cities: Porto (Portugal), Rotterdam (Netherlands), Norrköping (Sweden) and Trondheim (Norway). During the 3-year project, urban stakeholders, comprising representatives of the four cities (see Table S1) were involved from the start in the co-design process to capture the needs, context, and challenges of each city. Furthermore, campaigns with end-users, identified by the municipal stakeholders as citizens or professionals that might likely use the app to share and obtain information, contributed to the co-design process by providing insights into how the app can be used and what type of information can be obtained in a real live setting.

Scientists initiated the project with commitment from municipal stakeholders to co-design, test, and evaluate a climate service, with the aim of learning from and engaging with stakeholders (Meadow et al., 2015). To as large degree as possible, the project linked to existing processes and meeting forms of participating stakeholders and users, rather than initiating new forums.

In 2017–2018, the project team at each pilot met with relevant stakeholders, including representatives of regional development commissions, civil protection, and various municipal offices, e.g., Technical, Digital, Health and Care, Physical planning, Construction and Environment, Water and Waste management and Climate and Society (Table S1). While the format of the climate service was pre-defined at the proposal stage to be a citizen science mobile app that could integrate sensor information, the project team engaged with stakeholders to determine significant weather-related issues, sensitive areas, citizen groups, as well as what types of relevant sensor data to collect, and to identify existing sensor networks. Additionally, the interactions explored the type and format the eventual reported information would optimally have (texts, photos), and how the collected information could inform municipal information services e.g., as input in models and databases, platforms, initiatives, sensor networks, databases, apps or map services. Stakeholders in each pilot identified key weather-related issues

Table 1

Key elements of Co-produced climate service process principles applied in this study (Adapted from Vincent et al., 2018).

Collaborative	- Mode of collaboration between researchers, stakeholders, and end-users, referring to the method, intensity, and timing - Methods to identify the context for the climate service as well as for the involved stakeholders and end-users - Engagement levels and willingness to participate - Reflexivity throughout the co-design process
Inclusive	- Inclusion of relevant stakeholders and users, and their partnerships and networks - Inclusion of participants with different demands, responsibilities, experiences, perspectives and knowledge systems - Inclusion of non-scientific knowledge - Inclusion of marginalised or less powerful groups
Flexible	- Integration of multiple perspectives in the co-design of the climate service - Agile processes that allow adaptation of the co-design process - Allowance for response within the iterative process which includes continuous knowledge exchange and collaborative learning

e.g., heat and cold, heavy rainfall, seasonal ecosystem changes, drought, and strong winds, as well as related climate impacts (Table S1). In subsequent interactions, stakeholders explored a paper prototype, and participated in the testing of the CitizenSensing web application and interviews (see Table S1). Stakeholders could, hence, influence important parts of the service from focus to functionality.

A stakeholder interaction manual (Wilk et al., 2021) was prepared to guide the co-design process across the pilots to more systematically prioritize, perform and document the interactions and outcomes. It focused on I) stakeholder co-design of the citizen science climate service, II) end-user citizen science campaigns and III) stakeholder evaluations of the citizen science climate service and its potential for municipal use. The manual contains exercises describing the initiation, performance and assessment of stakeholder and end-user interactions to streamline and organize goals, priorities, and responsibilities across the pilot cities.

Stakeholders identified potential end-users, i.e., groups that could test the app including students, staff of home care and day activity services, as well as vulnerable groups, e.g., senior citizens (Table S1). Based on these suggestions, the project team performed end-user campaigns between March 2019 and November 2020 (Table S1). These lasted from one week to four months and involved different target groups. The campaigns focused on heat, flooding, and seasonal observations. End-users included secondary, high school, university and senior students and home care staff. At the conclusion of the project, eight municipal stakeholders were interviewed in the four cities i.e., Norrköping (2), Porto (3), Rotterdam (2) and Trondheim (1) in April–May 2021, for a final evaluation of the co-design process and to elicit their perspectives on the potential contribution of the collected data and the climate service.

The co-design process was assessed through the documentation of stakeholder interactions (e.g., workshop design, participants, outcomes), end-user reports (how the app was used, what was reported), and the final stakeholder interviews. Based on this data, we examined the co-design process of defining focus, content, and functionality of the citizen science climate service, use of the climate service in terms of what end-users reported and reflections of practitioners on the climate service, the knowledge that could be produced by employing it, and to what extent the climate service could contribute to urban climate resilience. The number of interactions and iterations varied according to stakeholder availability, consisting most often of 2–3 workshops accompanied by smaller meetings, consultations, and interviews. The interactions took place between November 2017 and May 2021 (see Table S1).

3.2. The CitizenSensing web application

The CitizenSensing web application¹ (Fig. 1) allows citizens to both report and share observations on local weather events and impacts, providing high-resolution information, access real time sensor data, view other citizens' reports and share and receive adaptation recommendations linked to their reporting. The CitizenSensing web application was designed to facilitate a high level of interactivity for different users and to enable sharing of knowledge and experiences. In this study, citizen sensing (Berti Suman and van Geenhuizen, 2020; Gabrys, 2017; Goodchild, 2007; Pritchard and Gabrys, 2016; Sheth, 2009) is used as a method to obtain citizens' observations and perspectives and to explore how citizens can contribute to knowledge about climate events and their impacts, as well as to increase the understanding of how local citizens perceive and respond to climate related risks in urban environments (Graça et al., 2021). A web portal was developed to allow a flexible

exploration and filtering of submitted reports during the co-design process and end-user feedback during or at the conclusion of campaigns (Navarra et al., 2021).

The prototype of the CitizenSensing web application contains lists of weather event types (low and high temperatures, drought, heavy rainfall, snowfall, storm, storm surges, strong wind, and seasonal observations, e.g., timing of plant growth), related impacts and personal comfort levels from which end-users can choose when reporting. Users are also asked to add a comment and photo to a report. Users could also access and refer to sensor data of temperature, air pressure and humidity from weather sensor stations, thereby making it possible to compare their own observations to nearby sensors. Sensor data was derived from existing sensor networks (Porto Digital, Netatmo network, WOW), as well as from sensors set up in some of the pilot cities by the project team. A user could view the profile of each pilot city which displayed current weather, temperature, and wind direction, a seven-day forecast, climate reference data of temperature and rainfall and a short description of average climatic conditions. The CitizenSensing web application features climate adaptation recommendations, relevant to the selected type of reporting, once a user has submitted a report. The app contains a gamification component, that displays a point score based on the number of submitted reports and inclusion of images and text, to encourage engagement and team competitions. The app content can be displayed in English, Dutch, Norwegian, Portuguese, and Swedish.

4. The co-design process

4.1. Collaborative co-design process

The project involved collaborative efforts between scientists, municipal climate adaptation stakeholders from different sectors, municipal employees, and citizen end-user groups. The stakeholder interaction manual (Wilk et al., 2021), guided the collaborative and flexible co-design process.

The project team aimed for a high level of collaboration and stakeholder engagement. Contact with municipal stakeholders was made in each pilot during the proposal stage. Researchers involved stakeholders that they had collaborated with previously, or to whom they were directed via earlier contacts. At the start of the project, the research team at each pilot initiated a dialogue with the contact person to identify a first set of stakeholders of relevance to the process. Additional participants were invited by these stakeholders to broaden the diversity of interests, viewpoints, and expertise. In Norrköping and Porto, existing municipal climate adaptation initiatives enabled an advantageous starting point since the project could connect and contribute to ongoing processes and discussions, strengthening the legitimacy of the process. Some stakeholders were interested but had difficulties to participate. For example, in Rotterdam, municipal stakeholders were involved in several ongoing research projects on climate adaptation which limited their time availability.

End-user campaigns included workshops, iterations, and test periods during which participants reported observed impacts with the CitizenSensing app. The campaigns aimed to engage participants in testing the functionality, design, and content of the app, but most importantly to obtain citizen perspectives on urban climate adaptations, through submitted reports of observed impacts and recommended adaptation measures. While the test and evaluation of the app provided insights that contributed to the co-design process, the submitted visual and text data allowed a deeper analysis of the role of the CitizenSensing app as a boundary object to engage citizens in climate events, impacts and adaptation actions to collaboratively produce and share knowledge. A Norrköping stakeholder considered the photos especially important to provide detail and understanding of the extent of observed impacts. As such, the app enabled sharing observations and perspectives on climate-related experiences and adaptation, across citizen and practitioner communities of knowledge, but also between practitioners with

¹ <http://citizensensing.eu>; the CitizenSensing web application can be accessed via the project website, but functions for reporting and accessing submitted reports are exclusively limited to campaign participants by means of a login function.

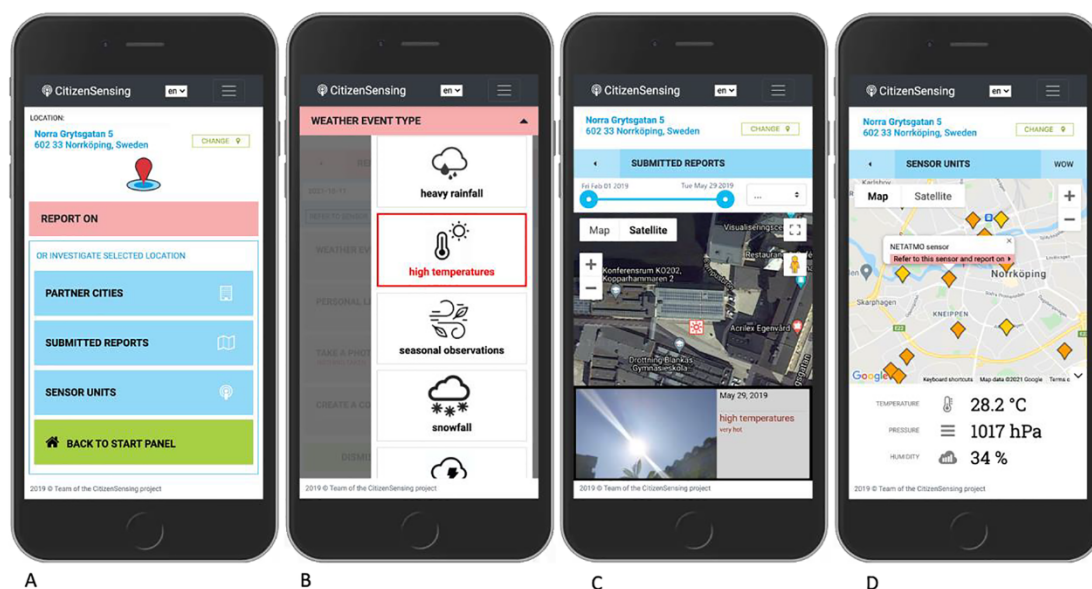


Fig. 1. The CitizenSensing web application, allowing the user to (A) submit a report for a specific location and explore the climate profile of a partner city; (B) select a weather event type and a related climate impact and add text or image to the submission; (C) view submitted reports by other citizens; (D) and explore sensor data for the selected location.

different responsibilities and perspectives on climate adaptation within the municipality. Citizen engagement with the app hence played an important role in the co-design process to iteratively assess the relevance of the reporting process and the app, and provided a basis for revisiting the app design and functionality throughout the co-design process. The transparency of the data collection process was critical to ensure that participants could contribute and contextualize their experiences of climate events and impacts and view reports of other citizens to increase the legitimacy of the process and outcomes. The Trondheim stakeholder pointed out the potential in citizen sensing for users to follow the data collection process as raw data accumulates instead of only being exposed to processed data. Trondheim and Porto stakeholders argued that the transparency of end-user reports positively contribute to their credibility. One of the Porto stakeholders added that credibility could be increased even further by ensuring a minimum number of reports per climate impact and site and the Trondheim stakeholder suggested that users could confirm other users' reports. Another Porto stakeholder considered long-term citizen reporting of weather impacts beneficial for validating the severity of past weather events for e.g., insurance companies or locating areas that are systematically affected by floods. The Trondheim stakeholder suggested that such a system would even be helpful for relaying single reports of holes in pavement or unstable soil conditions as locations of potential landslides.

As with stakeholders, the project team aimed for collaboration with diverse end-user groups. In all campaigns it was challenging to elicit and maintain engagement. Despite gaming and team competitions, students often stopped reporting if the topic was not directly related to their classroom learning. Similarly, during a longer home care staff campaign, only a few high scoring teams continued reporting to the end of the campaign, while teams with lower scores dropped out after a few weeks of initial engagement.

4.2. Inclusive co-design process

The process aimed to include a diverse group of stakeholders from the onset and included practitioners that worked in different sectors of the municipal organization, to outline how the CitizenSensing app can contribute to the collection of relevant data but also to the dissemination of relevant information to and among citizens. Stakeholders provided a diversity of perspectives on climate resilience, such as health, education,

vulnerable groups and environmental issues, as well as technical systems and infrastructure. Throughout the process, new representatives replaced others either temporarily or permanently, which contributed further to the diversity of perspectives included in the co-design process.

While stakeholders suggested potential end-users to be included in the campaigns (see Table S1), group types were not selected to be representative of the larger public but those linked to or with specific interest in climate issues and adaptation. The project team focused on senior citizens, carers of the elderly, disabled and people with special needs and 'recently arrived' migrant students, as these groups are considered vulnerable to adverse impacts of climate change (Gaskin et al., 2017; Holand et al., 2011; Polack, 2008; Rhoades et al., 2018). Secondary and university students were also chosen for their role as young citizens and future practitioners and decision makers. It was surmised that senior citizens would likely find the app challenging, but senior students in the Porto campaign were considered a suitable group as they were taking a university class on digitalization. While these students were interested in a campaign, limited digital proficiency greatly inhibited their reporting. In Norrköping, recently arrived migrant students had no difficulty with the technical elements, yet they required additional visits and language support to encourage their participation and experienced relevance.

The app was designed to provide end-users with climate-related information and other users' reports and recommendations of climate adaptation measures. In addition to a list of pre-defined weather events and impacts, the option, "other", allowed users to include their own categories, which enhanced the inclusion of new perspectives. The app prototype was tested with stakeholders and ten end-users in Norrköping and revisions were made based on their feedback on app design, technical functionality and content to increase its relevance and legitimacy.

We exemplify the inclusivity of the end-user co-design process with a typology of perspectives from one of the campaigns in Norrköping in summer 2019. While campaigns focused on seasonally relevant topics i. e., *high temperature* and *heavy rainfall*, participants could submit reports of any observed climate-related impacts of relevance with related adaptation measures. Reports ranged from examples of generic impacts related to *high temperature* or *heavy rainfall* to specific personal observations of e.g., experiences or adaptation recommendations. Five distinct types of reports were identified: (i) weather events with comments and/or images (ii) observed and personal experienced weather-

related impacts with comments and/or images; (iii) advice on adaptation measures linked to a weather event; (iv) selection of a weather event and/or impact without any comments or image, and (v) 'social media' reports, that did not refer specifically to any weather event or climate impacts. The last category mainly consisted of reports categorized as 'seasonal observations', with images of e.g., flowers, or general comments on personal activities without explicitly linking to weather or climate. While reports in categories (i)-(iii) provided deeper insights into participants' perspectives on impacts and adaptation measures, those in category (iv) provided information about generic app use, and data for cross examination in terms of spatial distribution of reported impacts, as well as a generic test of the app functionality (Navarra et al., 2021). Category (v) reports on the contrary pointed towards the challenge of having an app that allows the contribution of images and free text responses, which was similar to other social media platforms, where users share their experiences without a specific focus. While most options in the app invited reports on specific weather events and impacts, the 'seasonal observation' option provided the widest scope of reporting for different types of observations.

Category (i) observations commonly denoted an upcoming change of weather or noted weather conditions not referring to any specific impact (e.g., 'the rain is pouring down'). Category (ii) reports focused on current weather events and observed impacts. These types of reports were frequently accompanied by texts that specified the observation, hence supporting the overall design scope of the app. In the final interviews, two stakeholders in Norrköping specifically highlighted the importance of linking photos with specific locations to strengthen the relevance of the observations. Category (iii) reports similarly contributed to the assessment of the core objective of the app design, as participants not only reported on specific weather events as well as experienced climate impacts but also provided examples and recommended adaptation measures in text responses and accompanying images, such as 'very hot, make sure the elderly drink sufficient with water' or 'so hot, 28 degrees, you have to look for shade if possible', indicating the relevance from a personal or professional perspective, frequently featuring coping strategies. These specifically indicated that the app was experienced as more relevant by some users than others, e.g., when images and comments exemplified concrete challenges that the end-users met in their professional context. These reports not only provided insight into the types of aspects that were relevant to users, and how different impact categories could be interpreted, but also revealed design challenges (e.g., allowing reports without impacts), and additional aspects to be included in future developments.

4.3. Flexible co-design process

The process of co-designing a climate service demands a high degree of flexibility in every step of the process as ideas, expectations, and perspectives of what the climate service should contain, evolve during the process. The CitizenSensing co-design process allowed the inclusion of new perspectives when additional stakeholders joined the process or replaced other participants, e.g., the possibility of reporting on ecosystems and signs of changing seasons, or through campaigns with new end-user groups. As these events introduced additional options and requirements to the climate service, it was not only the process that needed to be flexible but also the climate service design, to easily encompass additions and adjustments of relevance e.g., new features and indicators.

The stakeholder interaction manual guided cross-pilot standardization, but flexibility and transparency were needed in each process to customize stakeholder interactions according to different preconditions, interests, and priorities and how the interactions developed. The stakeholders' and end-users' time availability greatly determined the type and extent of interactions as well as the number of iterations. Campaigns were organized to target key weather-related issues yet be flexible and adaptive to end-users' requests and availability. As

campaign introductions were held either during class or work hours, time constraints were heightened if end-users had difficulty to download the app, follow app instructions or understand terminology. This introduced on-the-spot changes to end-user meetings, to repeat instructions or solve technical issues.

To encourage flexibility in the climate service and enable reporting on a wide variety of climate-change related impacts, the category 'seasonal observation' enabled users to report on events such as the timing of the growth of plants. This gave additional options to contribute even when no extreme weather events or impacts were observed. However, this revealed the trade-off between flexible and inclusive design and targeted data collection. In the Norrköping campaign, the largest share of the reports was made in this category. While a significant share of reports neither provided additional comments or images nor referred specifically to any climate impacts category, the high number of reports did however contribute to a more robust app functionality assessment and indicated that including a gamification mechanism in the campaigns caused over-reporting. Reports that only provided a weather event or climate impact without text or image further provided an important dataset to assess the spatial and temporal distribution of reports, linkages between observations and sensor measurements, and revealed challenges that need to be addressed in terms of open and flexible data collection (Navarra et al., 2021). While stakeholders from all four pilots found the combination of sensor and citizen-based information to be important for increasing credibility, Rotterdam stakeholders pointed out the importance of correcting eventual bias of included sensor data. All stakeholders stressed the importance of integrating and linking climate services with existing systems.

5. Discussion

5.1. Barriers influencing the co-design process

While collaboration is an essential element in the co-design process, several related barriers inhibited the progress and outcomes (Table 2). One barrier frequently reported in participatory studies is stakeholder

Table 2
Barriers and Enablers for co-designing a citizen science climate service.

	Barriers	Enablers
Legitimacy Relevance	• Different perspectives of the purpose of citizen engagement activities • Varying and declining level of experienced relevance • Collaborative research is time-intensive and often disproportionate to research funding • Stakeholder/end-user time constraints • Gamification deters reporting by low-scoring end-user	• Experienced relevance of end-users or local processes • Integration with existing long-term climate adaptation processes, contacts, and networks • Extended spatial coverage and resolution of local climate-related data • Flexible design process to match stakeholder/end-user requests and limitations • Gamification sustains reporting by high-scoring end-users
Credibility Transparency	• Stakeholder turnover challenges the process • Time constraints for collaborative research • Data-bias from lack of reporting continuity • Limited language skills or digital proficiency • Standard cross-pilot app content adds complexity • Customization to city context limits comparability of outcomes	• Stakeholder turnover introduces new voices and perspectives • Flexibility allows easy inclusion of new user groups and perspectives • Simplified app design • Iterations of the product development and campaigns allows easy inclusion of new users • Standardization of process and app encourages comparability of outcomes

fatigue (Bracken et al., 2015; Gramberger et al., 2015). This was for instance observed in Rotterdam as the municipality was already involved in several research projects. In the case of end-users, some participants stopped reporting after an initially high engagement. Whereas this differed significantly between and within campaigns, clear targets, prizes, and competition triggered greater engagement by some end-users while the experienced relevance of climate impacts more strongly influenced the degree and length of the engagement for other users. The Trondheim stakeholder highlighted the difficulty of handling differing perspectives and expectations between municipal employees and citizens of crowdsourced data. For instance, despite supporting the relevance and possibility of widespread reports of events and impacts, the stakeholder expressed that citizens might expect immediate municipal response towards submitted reports.

Barriers related to stakeholder perspectives were linked to the engagement process itself. While the stakeholder engagement process, aimed for an inclusive and transparent process, the changing stakeholder representation affected process consistency.

As collaborative research processes are particularly time-intensive, and frequently disproportionate to research funding (Cvitanovic et al., 2015), time constraints affected the collaboration and inclusiveness of the co-design process in several aspects. While time constraints varied in each process, stakeholder interaction was frequently limited. End-users' time constraints limited the amount of time available for introducing the project and solving technical aspects, and the extent to which their feedback could be collected. In addition to workshops with several stakeholders, a flexible, more frequent contact with selected collaborators could support the process through more in-depth discussions on design choices and exploring possibilities and discussion on additional end-user groups and campaign feedback. Such smaller meetings however introduce challenges for transparency and legitimacy, if some stakeholders are more easily and frequently contacted and available than others.

Barriers in terms of including the perspectives of campaign end-users were related to the timing and introduction of the campaign, but also to the gamification element, and the fit between the campaign focus and the perceived relevance of the weather events, impacts or climate adaptation. Another constraint was that sometimes the targeted weather conditions did not occur during the campaigns, leading to confusion about what might be relevant to report. Furthermore, the standardization of the app categorizations across all pilots introduced complexity which may have affected usability. Rotterdam, Trondheim and Porto stakeholders considered the app categories and language to be inclusive but pointed out that they may be too complex for some end-users, for instance those with limited language skills.

5.2. Enablers influencing the co-design process

The research team made use of earlier contacts, networks and established relationships and entry points to key sectors and organizations, as pointed out in earlier studies that raised the importance of including existing communities and harnessing networks (Campbell 2016). Furthermore, working with existing community structures can positively contribute to transparency through greater outreach opportunities (Djenontin and Meadow, 2018).

The app and reporting process encouraged collaboration through the sharing of unique perspectives, and easy virtual collaboration in that end-users could participate on their 'own terms' - i.e., at any time and from any location, with the option of sharing recommendations based on their own experiences e.g., reminding others to drink sufficient amounts of water during heat waves. The inclusive campaign design enabled end-users to contribute easily and continuously, even when no extreme weather events or impacts occurred during the campaigns. The substantial number of reports in e.g. the Trondheim and Norrköping campaigns indicated that participating end-users found the app easy to use, which was also highlighted by one of the Norrköping stakeholders who

argued that the high number of reports indicated that the app was sufficiently easy to understand and navigate.

The submissions revealed that the topic was more relevant for some end-user groups for instance those that included images and comments that reflected concrete examples of impacts that posed challenges for them in their professional roles, e.g., heat waves during which the clients of the home care staff are more susceptible to dehydration and heat stress. The pattern of reports showed that frequently only a few top-scoring teams continued to report throughout the campaigns and follow-up discussions revealed that competition was a strong driving factor in prolonged reporting.

The basic and flexible app design enabled the inclusion of a wide variety of aspects and climatic conditions, that encompassed the interests and needs at the different pilots. As such, the iterative phases during the app development, including a paper prototype, test sessions of the first prototype and adaptation of the app content and design following early pilot testing, allowed the research team to easily include feedback from stakeholders and end-users and upgrade the service.

5.3. The 'Balancing Act' of Co-Design

Our analysis of the co-design process reflects several aspects that relate to prior studies in climate service development, participation theory and knowledge co-production processes. The barriers and enablers, revealed a 'balancing act' to navigate and negotiate different contexts and conditions at the pilots, as well as the interests, priorities, availability, perceptions and expectations of participating stakeholders and end-users. A reflexive approach (Fazey et al., 2018) throughout the collaborative process, engaging practitioners, citizens and researchers alike, is needed to foster awareness of aspects influencing the co-design process as well as the consequences of methodological choices.

The context of each pilot city defined what was possible to initiate and undertake, which in turn influenced the process and outcomes, including the availability, expertise and interests of the participating stakeholders. Flexibility was needed to adapt both research and climate service design to respond to the contextual setting of end-users and cities. Some aspects could be better addressed if relevant stakeholders are involved in the research-design phase (Mauser et al., 2013), yet the project time frame, as well as the inclusiveness principle, continually transform the stakeholder group, hence introducing new perspectives, expectations and demands on the climate service and project outcomes. Similarly, supporting structures such as stakeholder interaction guides or tools can align processes spanning several contexts yet co-design processes require a high level of flexibility from the research team as well as the climate service. As such, both the process and the service need to balance the scientific goals of the project with the emerging and shifting expectations and interest of participants, while simultaneously responding to and capitalizing on new opportunities as they emerge.

Throughout the co-design process, we observed to what extent the climate service played a boundary-crossing role in terms of reaching across sectors, issues and enabling collaboration and inclusivity between researchers, stakeholders and end-users. The concept of citizen sensing, as applied in this project, builds on a two-way communication between municipal authorities and citizens, and as such the climate service itself could play the role of a boundary object, allowing the different stakeholders within a municipality to 'share meaning, but also to learn about each other's perspectives' (Fox, 2011:72) in supporting dialogues on local climate impacts across sectors, when for instance identifying climate impacts to be included in the app. Similarly, citizens were enabled to explore and share experiences and recommendations related to climate adaptation between different end-user groups as well as with the municipal stakeholders by means of viewing the uploaded reports on the app or web portal. These interfaces, containing the submitted reports, together with selected categories of climate impacts, images and short texts hence provided a shared language allowing individuals with various professional, cultural and socio-economic backgrounds to

represent their perspectives and knowledge (Carlile, 2002; Fox, 2011). The open and inclusive structure of the app allowed end-users to report on a wide variety of issues, e.g. by means of including wider categories, and the option to include ‘other’ climate impacts, while sufficiently robust to ‘maintain a common identity across sites’ (Star and Griesemer, 1989:393). The app hence allowed an interaction that moved beyond crowdsourcing, towards bridging across a range of perspectives and experiences. As such, the app enabled communication by mediating between users and translating their knowledge and observations (Cash et al. 2003).

Challenges related to participation, citizen science and co-design processes, require balancing the interests, priorities and constraints of researchers and a diverse group of stakeholders and citizens. This diversity is essential to ensure legitimacy, relevance, transparency, and credibility, yet it introduces greater complexity to the practicalities of the process, which is particularly challenging in shorter research projects and reporting campaigns. For example, there were frequent time constraints of stakeholder and end-users, yet time is required to build trust and allow for deeper discussions between researchers and stakeholders and end-user engagement. Menzel et al., (2013) argue that if time and resources are limited, time should rather be allotted to the quality of processes than to increasing the degree of participation, yet this is a trade-off in terms of inclusiveness and legitimacy.

Gamification was found to elicit and prolong interest and engagement of some end-users but had the opposite effect on others. As gamification risks introducing a shift from intrinsic to extrinsic motivation as well as a potential data-bias, in terms of over-reporting by some participants, it might result in a decreased quality of the data, which could influence the legitimacy and credibility of outcomes (Lember et al., 2019; Tönurist and Surva, 2017).

A balance was sought between the standardization and customization of the co-design process. The stakeholder interaction manual supported standardization, a principal element in academic study to systematically explore processes and make credible comparisons, yet a certain level of customization was required to ensure legitimacy and relevance of the process and to match the needs and resources of stakeholders and end-users (Campbell et al., 2016). Furthermore, as Lember et al. (2019) emphasize, the use of digital tools in participatory processes does not necessarily lead to enhanced knowledge co-production, and careful consideration is required to aspects that might obstruct the intended process. While our results show several aspects in which the climate service could function as a boundary object e.g., by bridging the perspectives between urban practitioners with different sectorial responsibilities, we also identified a set of barriers to the co-design process, that might e.g., lead to data bias, or exclusion of certain groups of participants. Ensuring a collaborative and inclusive process hence requires a careful balancing of the interests of stakeholders, and the priorities and pre-conditions of citizens.

6. Conclusions

This study set out to explore the process of co-designing a citizen science climate service, analyzing empirical findings from collaborative processes with stakeholders and end-users in four European pilot cities. In conclusion, the study makes the following contributions:

Firstly, we identified aspects that enabled the co-design of the climate service, allowing for a collaborative, inclusive and flexible process. Specifically, our results point towards the need for a high level of flexibility to adapt to the perspectives and interests of stakeholders and end-users. The design of both the process and the climate service facilitated matching the participants’ requests, and the inclusion of diverse end-user groups as they were identified in the co-design process. Important enablers were the integration of the project with long-term local climate adaptation initiatives and networks, which was the case in Norrköping and Porto where the project team could take part in dialogues and activities of existing climate adaptation initiatives, and

clear relevance of the targeted climate impact to end-user groups. As a certain level of technical or language proficiency was observed as a barrier for user groups that could however greatly benefit from the climate service, more systematic involvement of potential mediators that are in regular contact with these groups might be a way forward.

Secondly, we identified barriers that affected the co-design process, in line with previous studies, such as constraints related to the time frame of the project and available resources, and availability of stakeholders and end-users. We observed that limited or declining engagement was sometimes linked to the gaming mechanism implemented to increase engagement, but also to longer campaigns, designed to capture extreme weather events. Exercises in the stakeholder interaction manual aimed to standardize pilot processes, yet the necessary flexibility and adaptation of processes at each pilot complicated cross-pilot comparisons of outcomes. Similarly, the standardized app format captured the complexity of the pilots’ climate conditions yet could have been a potential barrier to some users.

Thirdly, we argue that the citizen science climate service could function as a boundary object in that it facilitated the exploration of urban climate impacts among participating municipal stakeholders, citizens, and researchers, enabling knowledge co-production on urban climate resilience by providing a platform that bridges across different knowledge communities, for sharing perspectives on local impacts, personal experiences, and adaptation actions.

Finally, we conclude that co-designing a climate service that draws on local expertise, perspectives, experiences, and engagement calls for a carefully executed balancing act. A co-design process and climate service that contribute to urban climate resilience require an acknowledgement that the process will demand time, efforts, flexibility, and reflexivity by all involved partners.

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CRediT authorship contribution statement

T.-S. Neset: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **J. Wilk:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. **S. Cruz:** Methodology, Investigation, Writing – review & editing, Funding acquisition. **M. Graça:** Methodology, Investigation, Writing – review & editing. **J.K. Rød:** Methodology, Investigation, Writing – review & editing, Funding acquisition. **M.J. Maarse:** Methodology, Investigation, Writing – review & editing. **P. Wallin:** Methodology, Investigation, Writing – review & editing. **L. Andersson:** Methodology, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cliser.2021.100273>.

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